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MORNING-GLORY SHAFT SPILLWAYS: PROTOTYPE BEHAVIOR

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HYDRAULICS DIVISION

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MORNING-GLORY SHAFT SPILLWAYS: PROTOTYPE BEHAVIOR

J. N. Bradley,[1] M. ASCE

SYNOPSIS

According to available records, the first morning-glory shaft spillway was completed in 1896, but the design did not come into general use until the latter part of the 1920's. Since then, some 30 spillways of this type have been completed or are now under construction. As only 25 years have elapsed since completion of the first spillway, on which there is useful concrete information, it has not been until recently that a morning-glory spillway of any size has operated. Thus the designer has been forced to rely entirely on theory and the results of model studies. Unfortunately, model studies do not solve all of the problems involved, so an investigation was instigated in 1950 to collect information from spillways which have operated. The paper deals with the results of this investigation.

INTRODUCTION

A morning-glory shaft spillway consists of three essential parts: a collecting structure or the morning glory proper, a vertical or inclined shaft, and a horizontal tunnel. Usually a vertical shaft is used, and this is connected to the horizontal tunnel through a rather sharp 90° bend. There are only two cases on record where inclined shafts have been used. In some cases a stilling basin is constructed at the downstream end of the horizontal tunnel, while in other cases the horizontal tunnel discharges directly into the river.

The morning-glory spillway may operate with free flow or, designed properly, it can operate submerged. For free flow, the discharge characteristics are similar to those for a straight overflow dam section, where an increase in discharge is proportional to the three halves power of the head. When operated submerged, the flow characteristics change completely; an increase in discharge is then proportional to the square root of the head. If, however, a portion of the shaft flows full, the effective head will exceed the head measured above the crest of the morning glory. A point to be remembered is that once submerged flow occurs, a further increase in head on the crest results in a very limited increase in discharge. Thus, if a morning-glory spillway is designed to operate submerged, an additional factor of safety is advisable to guard against the spillway capacity ever being exceeded.

The morning-glory spillway is attractive in that it can often be constructed at less cost than other types, and it is readily adapted to dams in narrow, steep canyons. Where a diversion tunnel is used to conduct the river around the site during construction, it can also serve as a portion of the spillway tunnel later. When designed to operate submerged, this type of spillway is

1. Engineer, Bureau of Reclamation, Denver, Colorado.

well adapted to flood retention reservoirs where the flow downstream is to be limited.

The principal difficulty in design has been the fact that, until recently, no morning-glory spillway of any size has operated. Thus, the designer has been faced with the task of designing on theory and the results of model studies alone. From a hydraulic standpoint, this type of spillway is sound. The questionable factors are structural; namely, will the concrete or other material composing the curved surface of the vertical bend and the horizontal tunnel withstand the effects of the high-velocity water, will ice or debris present difficulties in operation, or will vibration or noise become objectionable?

With the design of the Hungry Horse Dam spillway, Figure 1, which will feature a total drop of 487 feet from headwater to invert of the horizontal tunnel, and the Heart Butte Dam spillway, Figure 21, which will consist of a morning glory designed for submerged flow with as much as 54 feet of head on the crest, the above questions take on added significance. For example, erosion of the tunnel lining in the Hungry Horse Dam spillway at the very high velocities contemplated would produce intolerable difficulties both in operation and maintenance. Vibration in the Heart Butte Dam spillway, embedded directly in the earth dam, would also create a serious situation with respect to settlement of both the spillway tunnel and the earth embankment.

In an attempt to partially clarify some of the unanswered design problems in the light of prototype experience, questionnaires were sent out to persons connected with morning-glory shaft spillways throughout the world. The texts of the questionnaires varied, but these four questions were common to all of them:

1. Has the spillway operated? If so, a log of operation would be appreciated.
2. Has erosion of the concrete been experienced in the shaft, the tunnel, or in the vicinity of the vertical elbow?
3. Has vibration or objectionable noise been noticeable in the structure during operation?
4. Has any difficulty been experienced with the passing of debris or ice?

The response and cooperation received in reply to this inquiry were excellent. Table 1 lists the spillways investigated, their location, reference material where available, and the names of the correspondents contacted.

Basis for Investigation

The purpose of the prototype investigation was, first, to determine the merits or shortcomings of present design practice with regard to morning-glory spillways and, secondly, to learn how the materials composing these structures withstand the forces imposed on them.

An incident occurred in 1941 which threw much doubt in the minds of engineers concerning tunnel spillways. The Arizona spillway at Hoover Dam, which has a fall of approximately 570 feet, went into operation for the first time in August 1941 and operated until December of the same year. The average flow during the 4-month period was 13,500 cfs. The maximum flow was 38,000 cfs, which lasted for but a few hours. At the conclusion of operations, a hole was discovered 115 feet long, 30 feet wide, and 45 feet below invert grade, immediately downstream from the vertical bend. The velocity

in the horizontal tunnel was approximately 170 feet per second. The spillway was designed for 200,000 cfs, so the average flow was about 7 percent of capacity. A full account of this incident was recorded in the Transactions of the A.S.C.E.[2] for 1947.

The Hoover Dam spillways are not of the morning-glory type, but the tunnel arrangement is similar to some morning-glory spillways. There are a number of theories as to what actually occurred at Hoover Dam, but none are conclusive. In short, there was misalignment of the invert of the vertical bend, there was evidence of cavitation, and a large hole at the base of the inclined shaft was indicative of impact and scaling. The Hoover Dam incident has ever since posed the question: If erosion can occur at the base of an inclined shaft, what can be expected in the case of a vertical shaft terminating in a sharp 90° bend.

The Investigation

As far as it is possible to determine, there are approximately 30 true morning-glory shaft spillways either in existence or under construction today. Only those spillways which have operated will be considered here. The first spillway of this type was built in 1896, designed by James Mansergh for the Blackton Reservoir, England. A second morning-glory spillway was constructed at the Front Reservoir for the Tynemouth Corporation, England, in 1908. The remaining spillways have been constructed since 1926. With the general introduction of model studies in this country and Europe in the 1920's, designers were able to take a more favorable attitude toward the morning-glory shaft spillway. It is interesting to note that model studies have been performed to aid in the design of practically all of the morning-glory spillways dating back to 1926. Unfortunately, model studies do not tell all that is desired.

A record of the morning-glory shaft spillways which have operated follows. These are discussed in the order of their completion so one may follow the evolution of this design as well as learn of prototype operation.

Davis Bridge Dam

The first morning-glory spillway in the United States was constructed at the Davis Bridge Dam on the Deerfield River near Whitingham, Vermont, completed about 1926. This spillway (Figure 2) was designed for a maximum discharge of 27,000 cfs, a head on the crest of 8 feet and a drop of 188 feet from reservoir to invert of horizontal tunnel. Reports indicate that this structure has discharged a number of times for short periods. The maximum discharge occurred in the September hurricane flood of 1938 when the water reached 6 feet on the crest. The computed discharge at that time was about 19,400 second feet, or 72 percent of capacity. The spill during this flood exceeded 10,000 second feet for 15 hours' duration. Inspection after the flood showed no appreciable erosion of the concrete in the horizontal part of the tunnel. An erosion pocket 3 feet wide by 6 feet long by about 3 inches deep was apparent at the vertical bend, but it was not certain whether this was caused by erosion due to velocity of the water, or spalling due to freezing and thawing of the concrete surfaces. In any event, the repairs were of a minor nature. The report goes on to say that all ice and debris which passed

2. Warnock, Jacob E., "Cavitation in Hydraulic Structures," a symposium, Transactions of the American Society of Civil Engineers, Volume 112, 1947, page 55.

over the crest; between the piers, has readily gone through the spillway. Logs and trees 50 to 60 feet long have passed through the spillway at times. The spillway makes some noise when it is in operation, but this can be heard only a short distance from the dam, and vibration appears to be no problem. Sixteen piers on the crest act as an antivortex device.

Taf Fechan Dam

A morning-glory spillway was completed at the Taf Fechan Dam in Wales in 1927. This spillway, Figure 3, was designed to handle a maximum discharge of 3,000 cfs for a head of 2.8 feet on the crest. The drop involved is 103 feet. The long sweeping curves of this early design are very suggestive of the morning-glory flower. Correspondence with the late W. J. E. Binnie, who acted as consultant, indicated that no trouble has been experienced with this spillway and no unusual repairs have been required. It is interesting to note the presence of the antivortex device, consisting of four small fins in this case.

Gibson Dam

The Gibson Dam spillway on the North Fork of the Sun River in Montana, a Bureau of Reclamation project, was completed in 1930. This structure (Figure 4) was designed for a maximum discharge of 50,000 cfs at a head of 20 feet over the crest and a drop of 180 feet. As originally constructed, the spillway had a free crest, but later the crest portion was altered and six radial gates were installed (Figure 5). The report states that up through 1947 the spillway operated several times. Upon inspection of the tunnel, two areas about 2.5 feet by 1.5 feet by 2 inches deep, prominently displayed erosion in the vertical bend. During the months of May and June 1948, a total of 435,000 acre-feet of water flowed through the spillway. The peak of the flow amounted to 13,100 second feet, or 26 percent of capacity. Water passing through the spillway at this time produced additional erosion of the areas mentioned above. The areas had increased to 5 feet by 3 feet, exposing several reinforcing bars. The spillway again went into operation in 1949, 1950, and 1951, reaching discharges of 4,500, 7,500, and 6,000 cfs, respectively. The tunnel and vertical bend have been inspected annually. The rate at which erosion has occurred has been slow but progressive. Repairs to the extent of patching were scheduled for 1952. From the irregular nature of the vertical bend, Figure 6, it would be unfair to tie down the responsibility for this erosion to any one cause.

The invert of the horizontal tunnel also showed wear, but this most likely occurred during diversion of the river at the time of construction. The report goes on to state that no ice has passed through the spillway, but large trees have passed through it during flood season with no apparent damage. Noise was reported to have been considerable, increasing with the discharge, but this was not particularly objectionable. There was no noticeable vibration, and the radial gates and piers prevented vortex action. The radial gates have been quite satisfactory.

Pontian Ketchil Dam

The Pontian Ketchil Dam in Singapore was completed in 1931. The spillway was designed for a discharge of 2,700 cfs, a head of 2.7 feet on the crest, and a fall of 60 feet (Figure 7). Information available states that this spillway has operated as expected, without objectionable erosion of any kind and without

unusual repairs. This spillway is located in the Malayan forest, where cyclonic storms occur of such intensity as to uproot large trees and carry them for considerable distances. Many of these have passed through the spillway without damage. An emergency spillway was provided in case the morning glory became partially blocked, but so far the emergency spillway has not been needed. The antivortex device consists of 15 piers on the crest.

Owyhee Dam

The Owyhee spillway in Idaho, Figure 8, completed in 1932 by the Bureau of Reclamation, was a daring design at the time. The capacity is 30,000 cfs, the maximum head on the crest for this discharge is 12 feet, and the water is dropped through a vertical shaft, 320 feet. A flood occurred in 1936 in which 300,000 acre-feet of water was passed in 3 months. The maximum discharge recorded was 15,000 second-feet, or one-half capacity. Since then, smaller discharges have passed through the spillway frequently. A flow of 6,600 cfs was recorded in 1951. The greatest flood occurred in 1952, when the spillway operated for over a month. The maximum discharge through the spillway was 20,000 cfs, or 67 percent of capacity. Inspections of the spillway have been conducted frequently since the spillway first operated in 1936; the latest inspection was made after the 1952 flood. This report states that the spillway shaft appears to be in excellent condition. There is no evidence of wear, and the form board marks still show on the concrete surface. The invert of the vertical bend shows only slight surface wear, Figure 9, the maximum probably does not exceed one-quarter of an inch in depth. At the time of the inspection, water was standing in the tunnel approximately 7 feet deep, so it was impossible to inspect the lower portion of the elbow except by probing. Probing with a piece of 1/2-inch pipe indicated no cavities or sign of excessive wear at the base of the vertical bend. As nearly as could be determined, the surface of the concrete in this area is not smooth, but the roughness probably does not exceed 1/4 to 1/2 inch in depth. The invert of the horizontal tunnel was also inspected by probing. No signs of excessive wear were found in this area, and the surface of the concrete appeared to be of about the same roughness as that observed at the elbow. No evidence of vibration has been apparent during spillway operation, and the jet does not flutter even with the gate in a raised position. Incidentally, a single pier controls the vortex action and also houses the ring gate operating equipment.

As this spillway is unusual so far as size is concerned, a few of the operating characteristics will be mentioned. For heads of 1 to 2 feet over the gate, the water falls in a solid sheet toward the center of the shaft, apparently entraining air faster than it can be released at the outlet end of the tunnel. This causes the pressure to increase until it is sufficient to break back; then air emerges with sufficient force to carry spray 50 or 60 feet above the level of the gate, Figure 10. This phenomenon occurs sometimes as often as once every 5 minutes, depending upon the tail-water elevation. For heads less than 1 foot on the crest, entrained air can apparently move back up the spillway shaft unhampered. For heads greater than 2 feet, the air pressure is not sufficient to break back and the air is forced through the outlet end of the tunnel, causing spray to be thrown high into the canyon. The action is directly related to the tail water, as a rather large tail-water depth causes a jump to form in the tunnel for most discharges.

Reports indicate that the ring gate on the spillway, Figure 11, and the controls have operated smoothly at all times. The ring gate was designed for automatic operation, but it was soon learned that manual operation was to be

preferred. This is the only spillway with a ring gate at the present time; however, a similar installation will be used on the Hungry Horse Dam spillway.

The Silent Valley Dam

The spillway for the Silent Valley Dam, Figure 12, was designed for a capacity of 2,600 cfs, a head of 2.3 feet on the crest, and a fall of 55 feet. Apprehension that erosion might occur caused the designers to line the vertical bend with cast iron. The report states that the spillway has operated several times, as expected, without any unusual erosion or repairs.

Manuherikia Falls Dam

The Manuherikia Falls spillway in New Zealand, Figure 13, is designed for 15,000 cfs, a fall of approximately 96 feet, and a head of 6 feet on the crest. This spillway has passed several small floods since its completion in 1935, aggregating about 2 feet of head on the crest besides a moderately large one in November 1948. In 1948 the spillway passed a maximum flow of 5,000 cfs, representing one-third of capacity. It is reported that erosion has occurred on the crest curve of the morning glory at the construction joints. There are also signs of wear at the circumferential construction joints in the vertical shaft to about 25 feet below crest level. At these joints some of the concrete has been eroded to a depth of about 3 inches, while a few patches on the surface have been removed to a depth of approximately three-quarters of an inch on areas up to 3 square feet. It is stated that frost action may have caused some of the erosion, there being seepage through the rock surrounding the spillway. Wear is also apparent at construction joints (up to 3 inches) at the vertical bend and in the horizontal tunnel for some 100 feet downstream. There has also been a general wearing of the bottom of the horizontal tunnel up to approximately 1 inch, but some of this occurred while the tunnel was being used for stream diversion during dam construction. The report suggests that construction joints should be avoided at the crest and also in the vicinity of the vertical bend in the tunnel. Very little debris or ice has passed through the spillway. Six piers serve to counteract vortex action.

Regadera Dam

Regadera Dam, which forms a reservoir for the city of Bogota, Columbia, was completed about 1935. The morning-glory spillway in connection with this dam, Figures 14 and 15, was designed for a maximum discharge of 15,000 cfs, with a head of 9 feet on the crest, and a total fall of 107 feet. This spillway has operated approximately 9 months out of every year since 1938. It is approximated that during this time approximately 800,000 acre-feet have passed through the spillway. A maximum discharge occurred in 1943 which was estimated to be approximately 5,670 cfs, or 38 percent of capacity. From November 1938 to November 1952, there were 78 days of operation in which the head over the crest exceeded 1.3 feet, and of these 78 days, the spillway operated 4 days with heads greater than 3.3 feet. There has been a general roughening of the surface at the base of the vertical bend, as can be seen in Figure 16. The vertical shaft is in excellent condition, but the invert of the horizontal tunnel shows erosion amounting to approximately 1 inch in depth. However, water flows through the horizontal portion of the tunnel approximately 75 percent of the time and this could carry a limited amount of

abrasive material. The report states that, in general, debris has passed through the spillway without difficulty. In 1943, however, some logs and debris lodged across the piers of the spillway and it was necessary to lift this material out with cables. It was reported that during one night of this flood, a great deal of vibration was noticeable and the noise was louder than usual. This could have been caused by debris blocking a portion of the spillway. No vibration has been reported before or since this incident.

Burnhope Dam

The spillway at Burnhope Dam in Durham County, England, Figure 17, has a capacity of 2,600 cfs, with 2.7 feet of head on the crest and a fall of 106 feet. The vertical bend in the Burnhope spillway was purposely lined with case iron to prevent erosion. One moderate flo of 1,400 cfs, or 55 percent of capacity, has been recorded with no undesirable operating conditions or damage. In this design, a curtain wall extends across the center of the spillway parallel to the horizontal tunnel.

Kingsley Dam

The spillway for the Kingsley Dam of the Central Nebraska Public Power and Irrigation District is shown in Figure 18. The spillway is designed for a capacity of 54,000 cfs, with a head of 28 feet on the crest and a fall of 148 feet. This spillway has been in operation many times since 1947. During 1951 the gates were used to pass the water for irrigation and power for practically the entire year. The maximum discharge has been approximately 4,500 cfs, or about 8 percent of capacity. The vertical bend and tunnel show no perceptible wear, and there has been no opportunity to pass debris or ice through the spillway, as the flow has always flowed under the tractor gates. The report states that no difficulties have been encountered in connection with the operation of these high tractor gates.

Jubilee Dam

The spillway at the Jubilee Dam, Figure 19, the largest English spillway up to this time, has a capacity of 17,000 cfs for a head of 9.4 feet on the crest and a drop of 245 feet. There was evidently some concern as to the advisability of dropping water 255 feet into a vertical shaft, which is evidenced by the introduction of the inclined tunnel. The only information received on the Jubilee spillway states that it has operated as expected. Discharges have been small, or moderate, and no erosion is reported. This is the first spillway in which special air venting has been employed in the shaft. A curtain of water tends to seal the tunnel at the entrance to the inclined shaft; thus, an air duct was provided in the inclined portion of the tunnel. It is interesting to note that the curtain wall in this spillway is normal to the one on the Burnhope spillway.

Lady Bower Dam

The Lady Bower Dam in Derby County, England, completed in 1944, utilizes two similar morning-glory spillways, Figure 20. Each spillway is designed for a capacity of approximately 10,000 second-feet, with a head of 6.5 feet on the crest and a fall of 128 feet. Several floods have passed over the spillway--in fact, three heavy storms occurred before the spillways were completed. The discharges through the spillways have been 1,240 cfs in 1947,

539 cfs in 1948, 310 cfs in 1949, 1,520 cfs in 1950, 1,460 cfs in 1951, and 2,310 cfs in 1952. It is not certain, but it is assumed that these discharges should be divided between the two spillways. The report states that the tunnel and vertical bends on both spillways were inspected in 1951 and on several precious occasions. The only sign of erosion was at the inside of the vertical bend at about the midpoint. This involved an area of about a yard square and amounts to little more than roughening of the concrete surface. The spillway has passed small amounts of ice, but the radial piers on the rim of the spillway prevent the passage of any large quantity, particularly when the ice is thick. Only during the last stages of thaw does any ice find its way down the spillway. It has been noted that when the spillway is discharging heavily, the cascade of broken water falling down the shaft acts as a sort of air pump and produces an air current charged with spray, which discharges out the lower end of the tunnel in considerable volume. It is stated that, contrary to expectations, the discharge is slightly greater for a given head with the stepped morning glory than with a smooth one. In conclusion, Mr. Hill states that the spillways have proved a highly efficient method of discharging overflow water from the resorvoir, and he considers them entirely reliable for that purpose.

Lumot Dam

The spillway at the Lumot Dam in the Philippines was completed in 1949. Unfortunately, the drawings for this spillway were lost in transit. The spillway is designed for a capacity of 7,060 cubic feet per second. The spillway operated intermittently from November 28, 1951, to March 1, 1952. The maximum discharge was 690 cfs, or approximately 10 percent of capacity. There has been no noticeable erosion throughout the tunnel lining. No debris has passed through the spillway, noise has been unnoticeable, and no vibration has been observed.

Heart Butte Dam

The Heart Butte Dam in North Dakota, Figure 21, was constructed by the Bureau of Reclamation and completed in 1949. The spillway is different from those preceding in that it is designed to operate principally submerged. The capacity is 5,600 cfs for a head of 54 feet on the crest, and the water falls 113 feet to the invert of the horizontal tunnel. Free flow occurs for heads up to 6 feet, while submerged flow occurs for heads greater than this amount. A large vortex forms for heads from 6 to 20 feet, while for heads from 20 to 54 feet, vortices are either small or nonexistent. The fixed piers on the crest serve to break up the large vortex into a number of smaller ones, reducing fluctuations in discharge and resulting in improved flow conditions.

The spillway passed a major flood in 1950, less than a year after the dam was completed. It operated for approximately 1 month and passed 148,000 acre-feet of water. The maximum flow into the reservoir during the flood was 24,000 cfs, while the maximum discharge through the spillway amounted to 3,800 cfs. An inspection after the flood showed erosion at two points in the vertical bend. In each case the eroded areas were about 8 inches in diameter and a maximum of 1 inch deep. Casts of this erosion are shown in Mr. Peterka's paper.[3] A second flood was experienced at the Heart Butte Reservoir

3. Peterka, A. J., "Performance Tests on Prototype and Model for Heart Butte Dam Morning-Glory Spillway."

in 1951. The spillway again operated for the greater portion of a month at a maximum discharge of approximately 3,000 cfs. Casts of the erosion in the vertical bend were again made after the second flood, and it was found that there was practically no difference in the casts taken in 1950 and 1951.

The spillway is not noisy and there is no noticeable vibration, but it has passed a large amount of ice and debris. In 1950 the ice on the reservoir was 12 inches thick and in 1951 it was 36 inches thick. As the flood occurred during thaw, much of this ice passed through the spillway, together with large timbers and debris.

Shade Hill Dam

The Shade Hill Dam, Figure 22, another Bureau of Reclamation project, was completed in 1950. This is another retention reservoir, and the spillway is designed to operate submerged. The spillway is designed to pass better than 5,000 cfs for a head of 40 feet on the crest. If the head increases above 25 feet, an emergency spillway also goes into operation. A flood filled the reservoir in the spring of 1951 and the spillway operated for about 1-1/2 months. The maximum flow through the spillway was 1,020 cfs for a head of 26 feet over the spillway crest, while the maximum discharge flowing into the reservoir was 33,250 cfs. After the flood, plaster casts were made of the invert of the vertical bend, but these showed no noticeable erosion. The tunnel and the vertical shaft were also in excellent condition.

During the flood, a boom which was contrived of oil barrels and cables partially went through the spillway, along with draftwood, timber, and ice, which was from 4 to 6 inches thick on the reservoir. A large dislodged tree, some 18 to 20 inches in diameter, with roots and branches, was observed going over the spillway. While operating submerged, a large vortex persisted over the spillway but there appeared to be no detrimental effect caused by it.

Akongtien Dam

The Akongtien Dam in South Taiwan was completed in 1951. The spillway was designed for a maximum discharge of 3,250 cfs, with a head of 11.5 feet on the crest. The drop from headwater to invert of the horizontal tunnel is approximately 81 feet. The spillway discharged for 5 and a fraction days in 1952, with a maximum discharge of 1,000 cfs, or approximately one-third of capacity. The volume of water passed was approximately 27,300 acre-feet. The report states that no erosion could be found in the shaft, vertical bend, or horizontal tunnel. This spillway operates submerged at about half capacity. Vibration was unnoticeable and noise was not objectionable. Very little debris passed over the spillway during the flood.

CONCLUSIONS

From the foregoing prototype information, it can be said that about half of the 16 spillways that have operated have undergone a fair test. The results of the investigation are by no means conclusive, but they are extremely encouraging. In summing up the foregoing, it can be said that in no case has erosion of a serious nature occurred in any of the spillways investigated. Of particular importance is the report from the Owyhee Dam, which has operated often, once at half capacity and once at two-thirds capacity. This is definitely the most adverse operating condition so far experienced with a morning-glory spillway dropping the water for over 300 feet vertically, yet nothing but roughened surfaces has developed. There is good reason to believe that the erosion reported

at the vertical bends on several of the spillways can be attributed to logs and objects falling down the shaft, to poor surface concrete which has scaled off by the high velocity water, or to spalling due to freezing and thawing.

Vibration, noise, and vortex action have been found not objectionable in any case. It is possible, however, that unsymmetrical loading of the spillway with debris can produce vibration, as was surmised in the case of the Regadera spillway.

Several recommendations have been suggested in the correspondents' letters and these will be mentioned here:

First, Mr. Ridley of New Zealand recommends that construction joints be eliminated in the morning-glory portion of spillways, as objectionable erosion was experienced in his case.

Secondly, several correspondents suggested that construction joints be eliminated in the vicinity of the vertical bend, and that particular care be taken with form work to eliminate offsets in this curved surface. Some went so far as to recommend grinding of the invert surface throughout the vertical bend.

Thirdly, approximately one-third of the spillways investigated showed considerable leakage at construction joints in the shaft and in the horizontal tunnel. This leakage is objectionable from the standpoint of frost action, inspection, and repairs. Also, large cavities can be formed around the tunnel lining where water has transported material through the construction joints. It was therefore suggested that rubber waterstops be considered in future designs.

To date, the best method known for coping with erosion caused by high velocities in morning-glory spillways lies in maintaining smooth surfaces, outlawing misalignment, and eliminating construction joints in vertical bends. It stands to reason that a roughened surface is more susceptible to scaling, impact forces and cavitation than a smooth one when exposed to high-velocity water.

It is believed that this paper will enable the designer to view morning-glory spillway design with more confidence than has existed in the past. Discussions will be appreciated on other morning-glory spillways which have operated.

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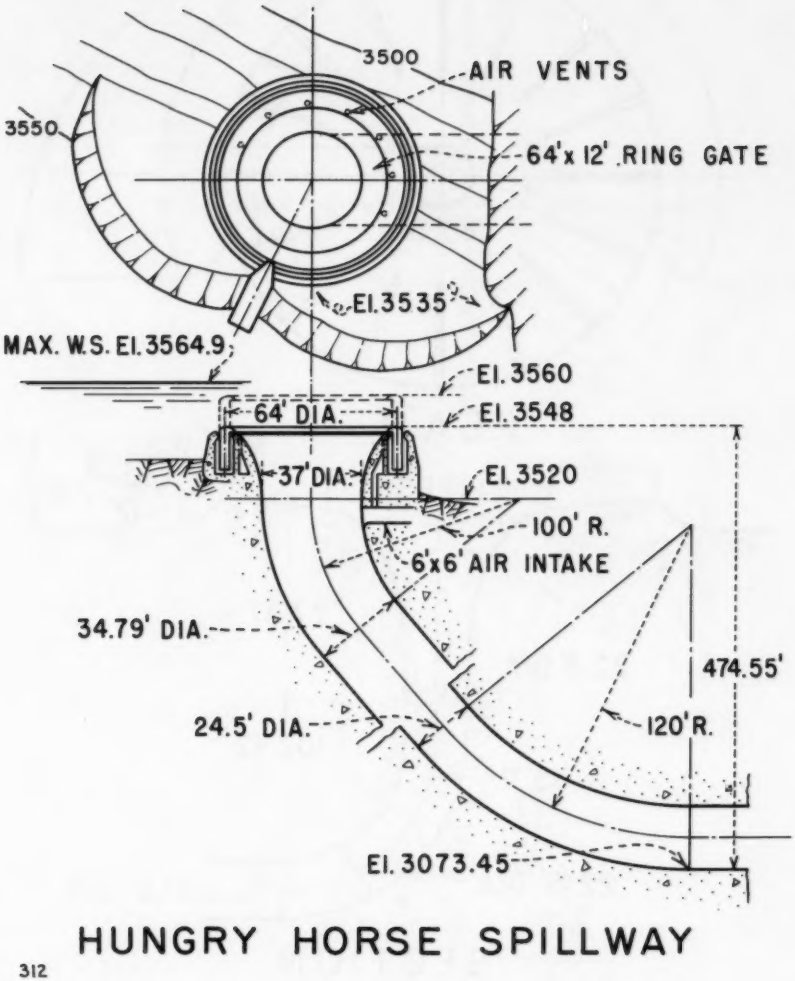
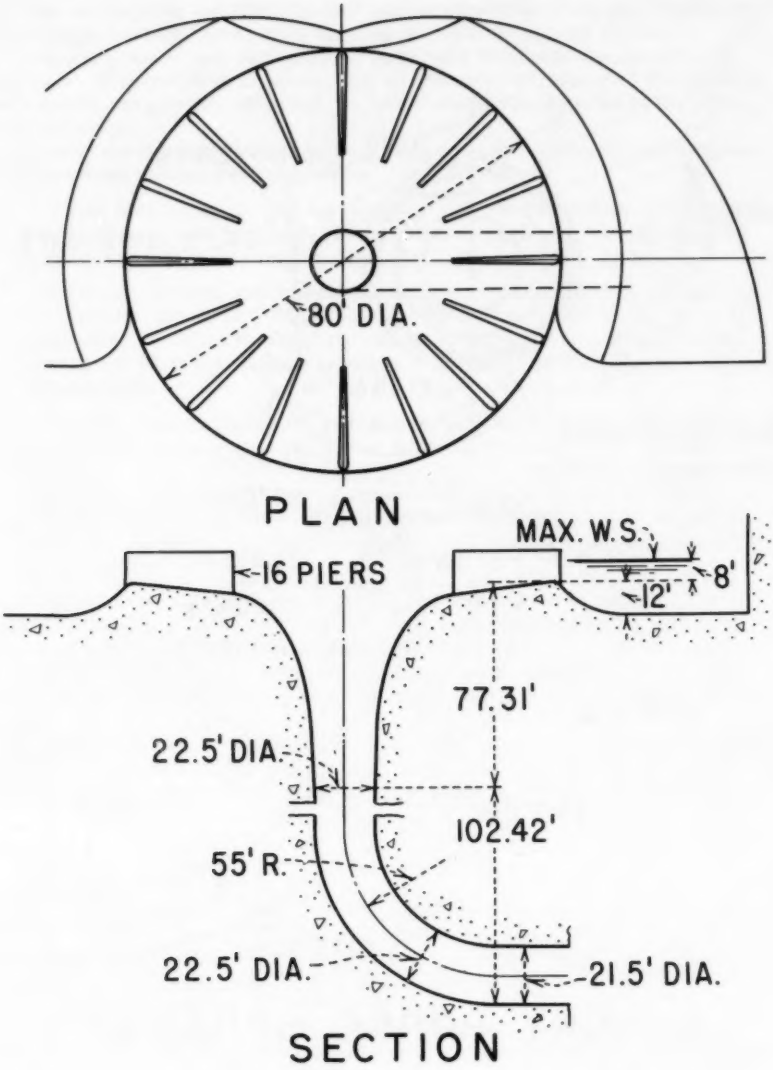


Figure 1.—Spillway—Hungry Horse Dam



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DAVIS BRIDGE

Figure 2.--Spillway--Davis Bridge Dam

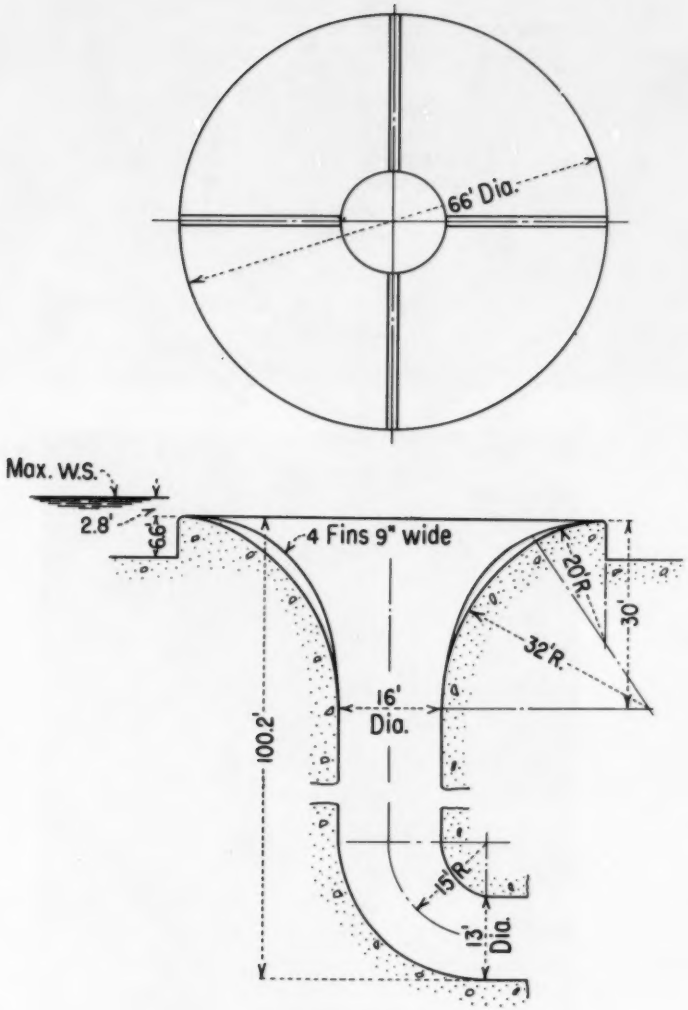


Figure 3.--Spillway--Taf Fechan Dam

TAF FECHAN

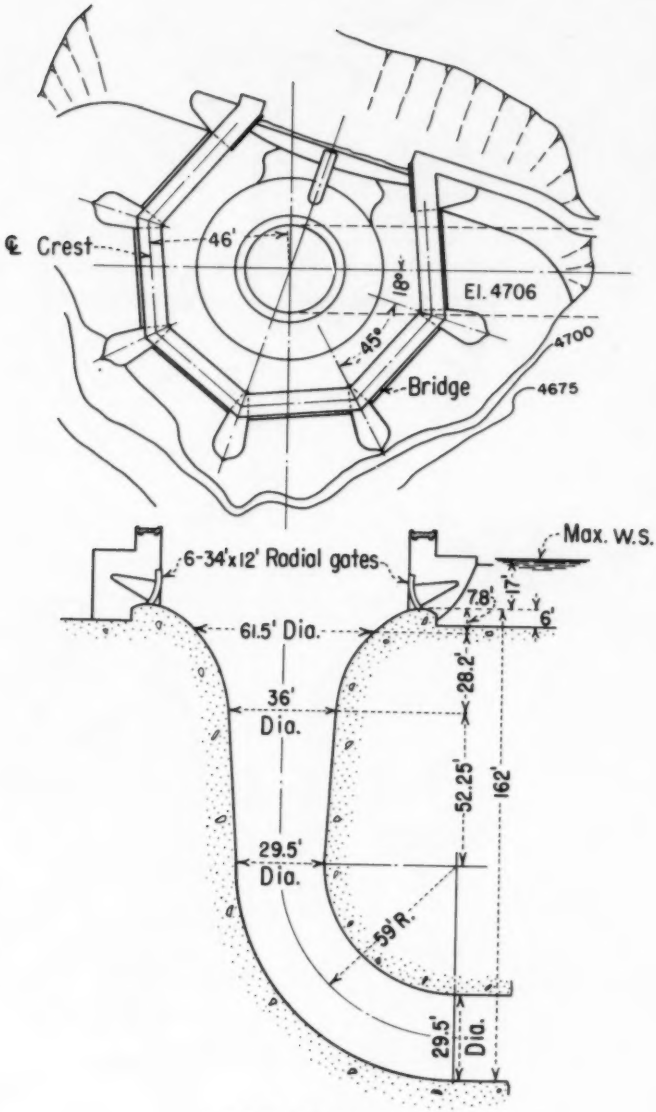


Figure 4.--Spillway--Gibson Dam

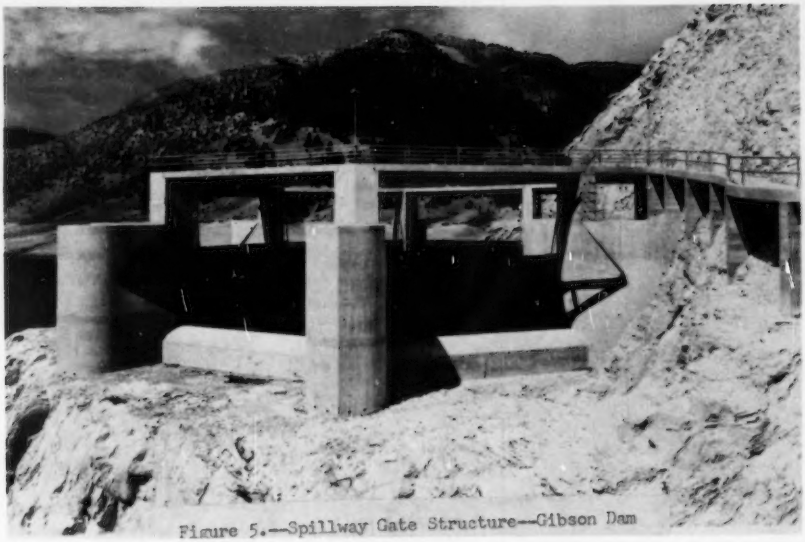
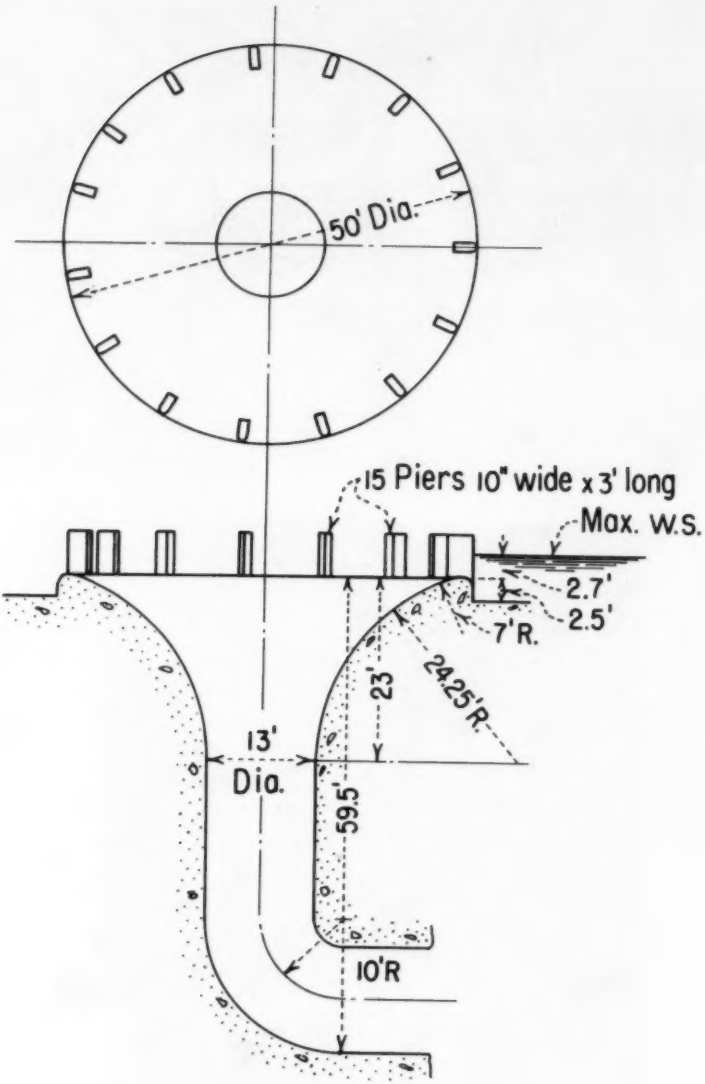


Figure 5.--Spillway Gate Structure--Gibson Dam

Figure 6.--Bend at Base of Vertical Shaft--Gibson Dam Spillway



PONTIAN KETCHIL

Figure 7.—Spillway—Pontian Ketchil Dam

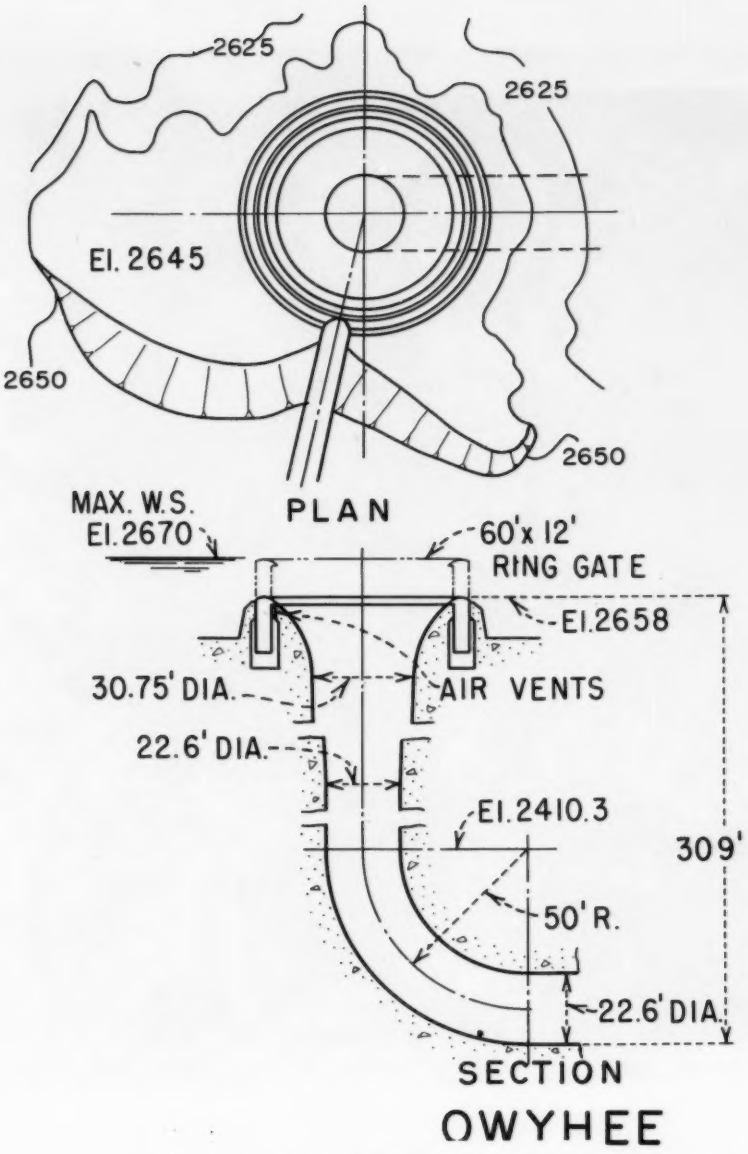


Figure 8.—Spillway—Owyhee Dam

Figure 9. Upper Portion of Bend at Base of Vertical Shaft—Owyhee Dam

Figure 10.---Owyhee Dam Spillway Operating with 1.5 Feet of Head on the Crest

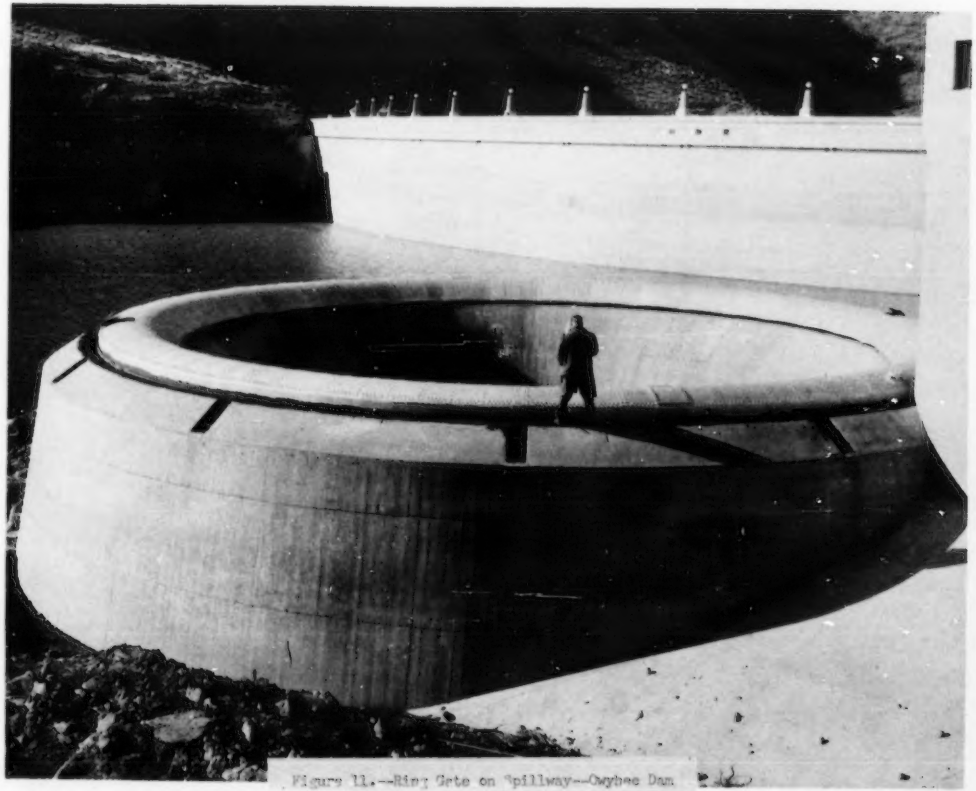
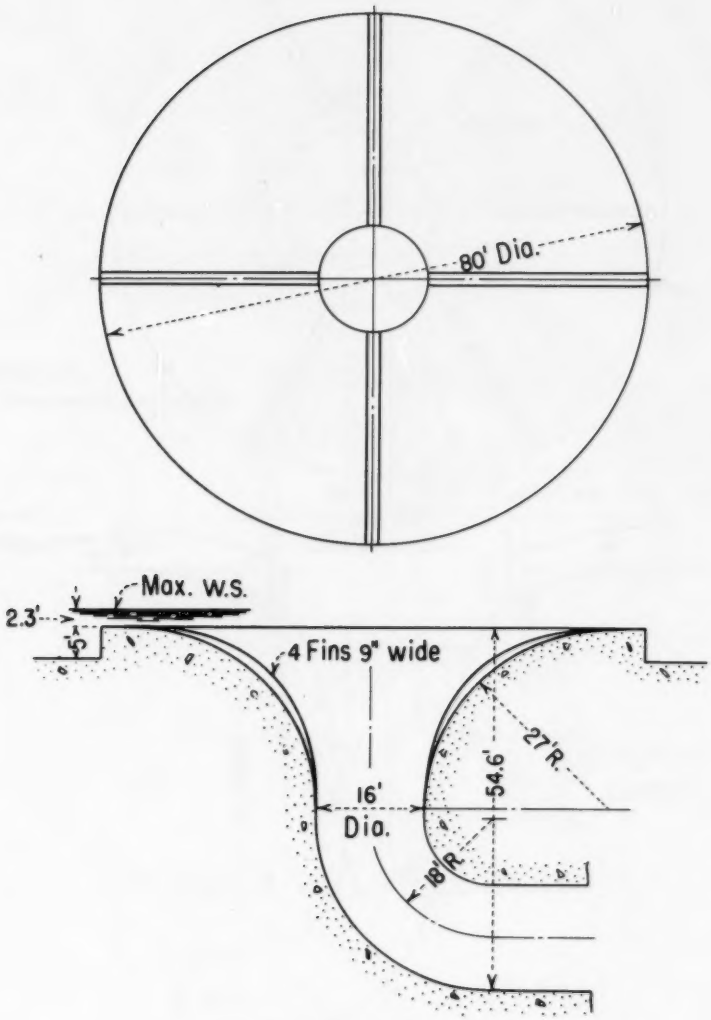
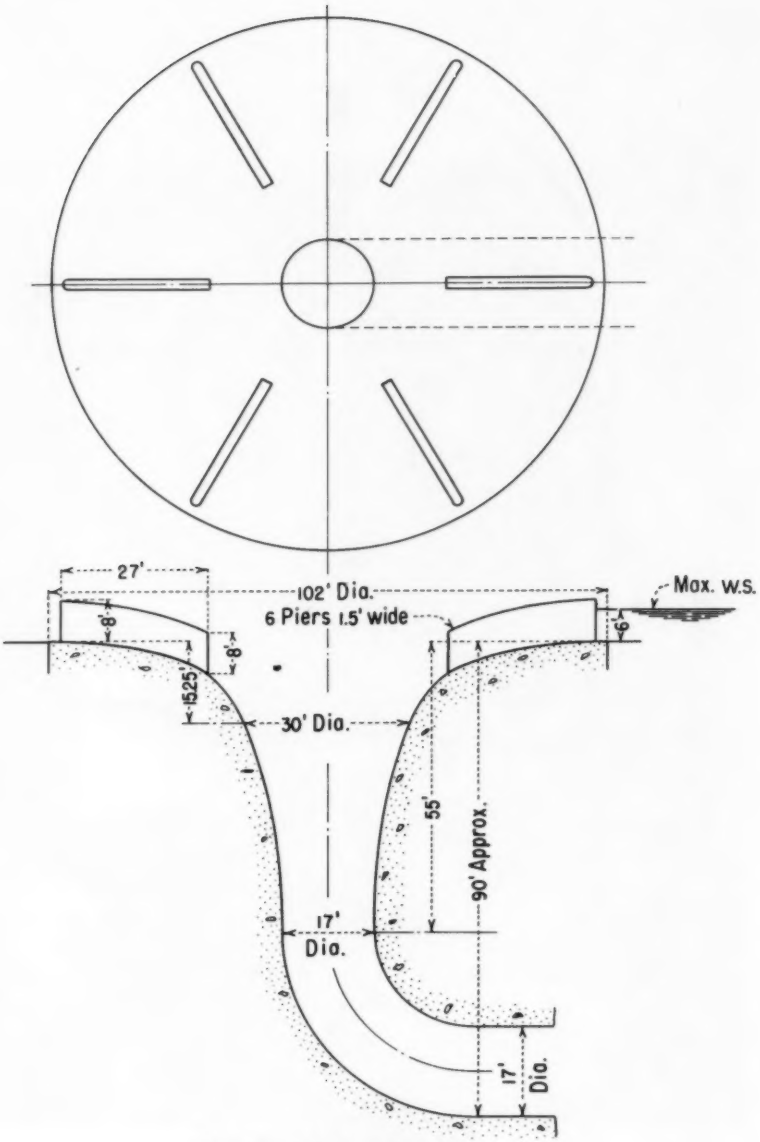


Figure 11.--Ring Gate on Spillway--Owyhee Dam



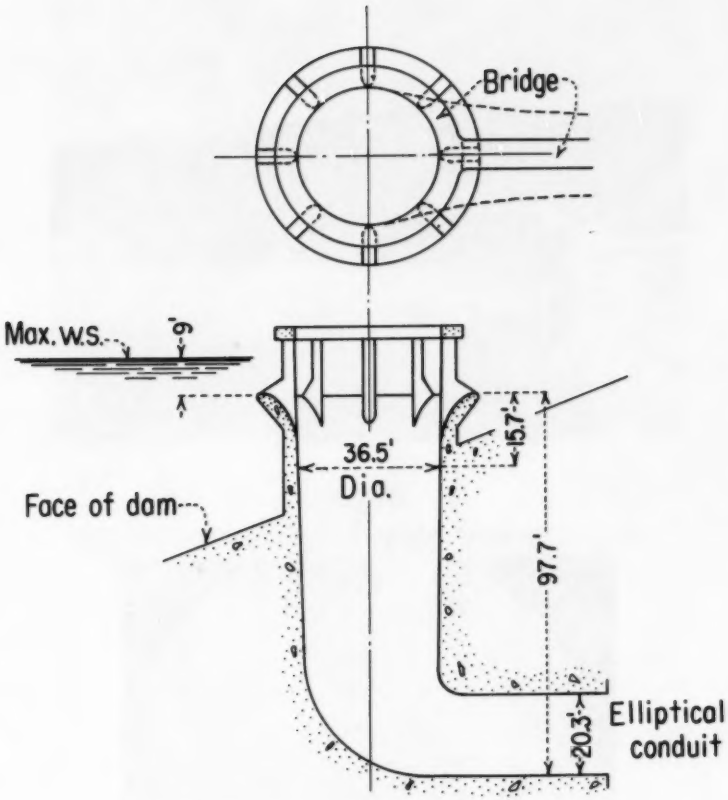
SILENT VALLEY

Figure 12.—Spillway—Silent Valley Dam



MANUHERIKIA FALLS

Figure 13.--Spillway--Manuherikia Falls Dam



REPRESA DE LA REGADERA

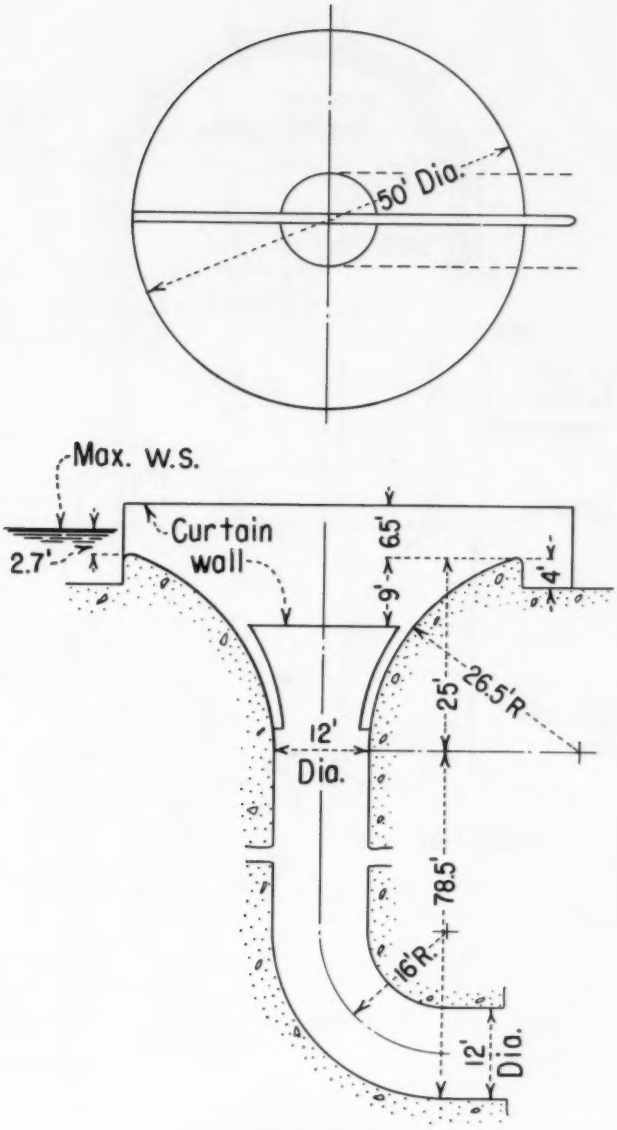
Figure 14.—Spillway—La Regadera Dam

Figure 15.

-Entrance, Piers and Bridge--La Regadera Dam Spillway

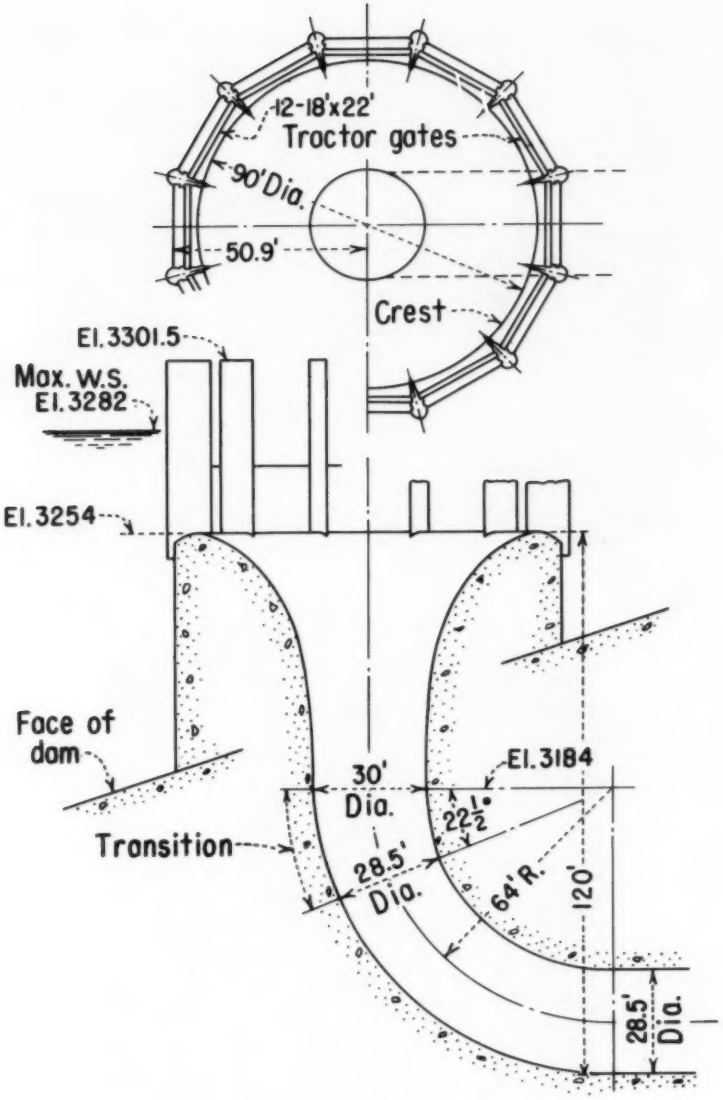
Figure 16.-

-Bend at Base of Shaft--La Regadera Dam Spillway



BURNHOPE

Figure 17.—Spillway--Burnhope Dam



KINGSLEY

Figure 18.—Spillway—Kingsley Dam

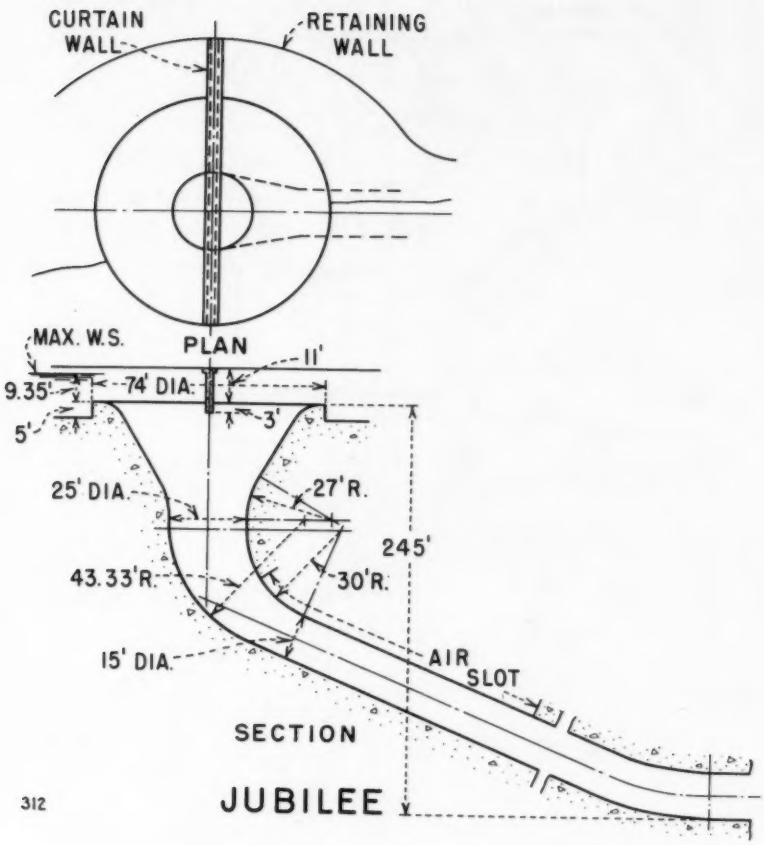
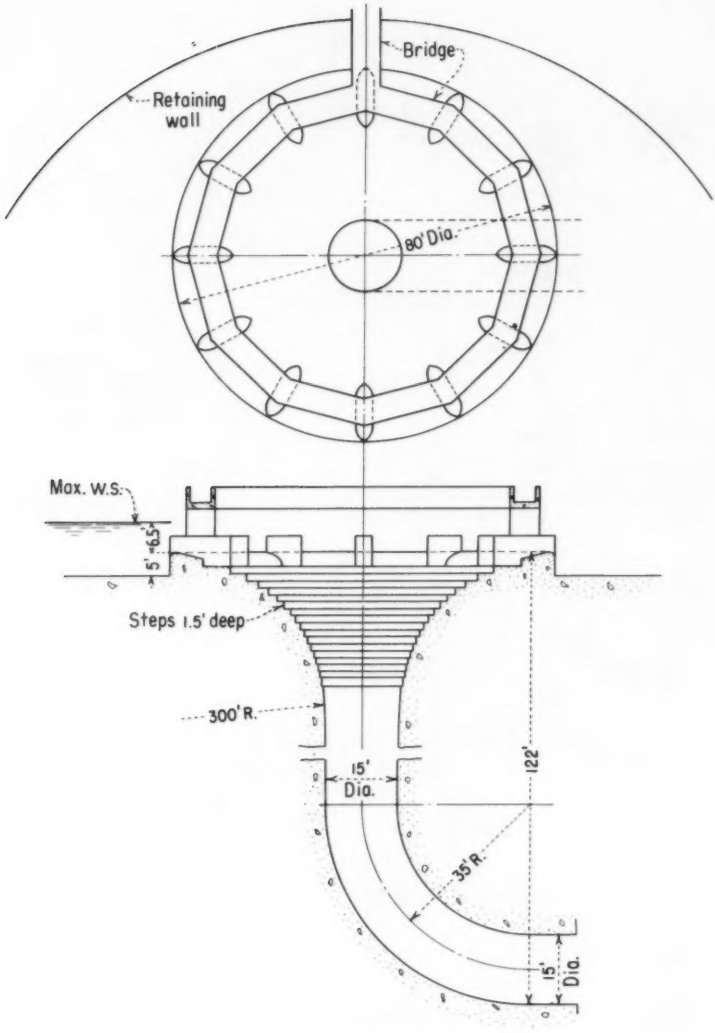
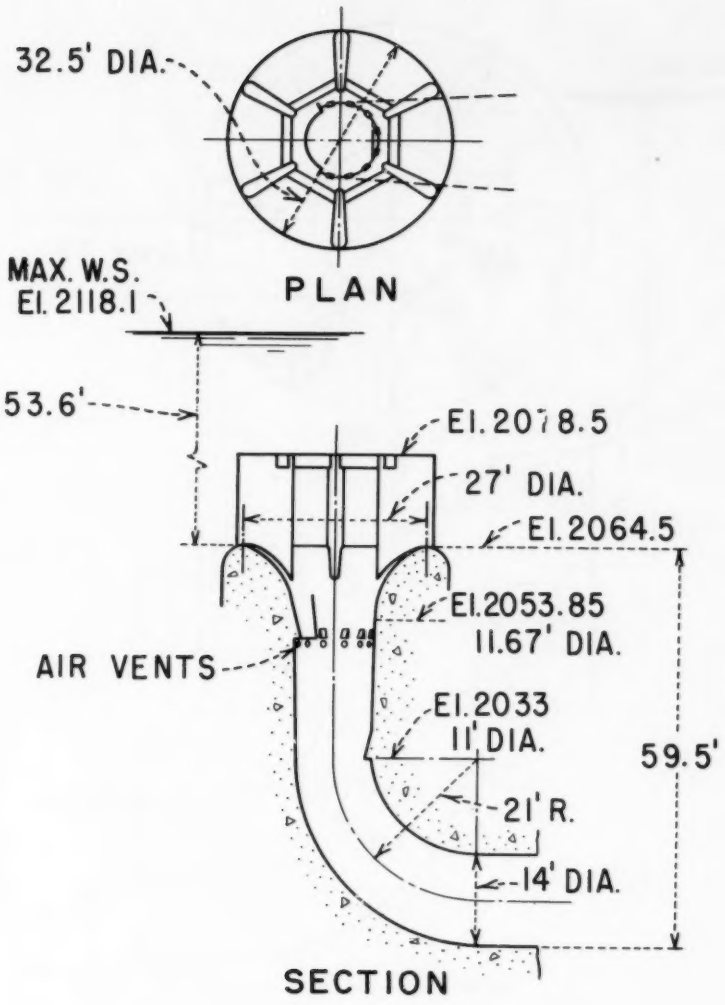


Figure 19.--Spillway--Jubilee Dam



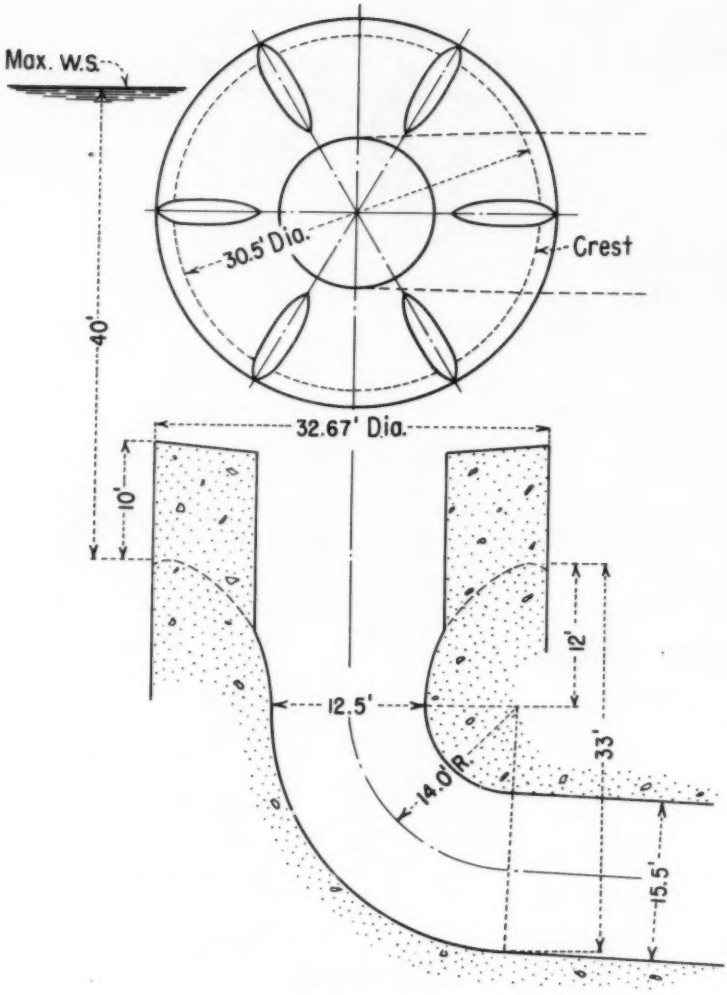
LADYBOWER

Figure 20.--Spillways--Ladybower Dam



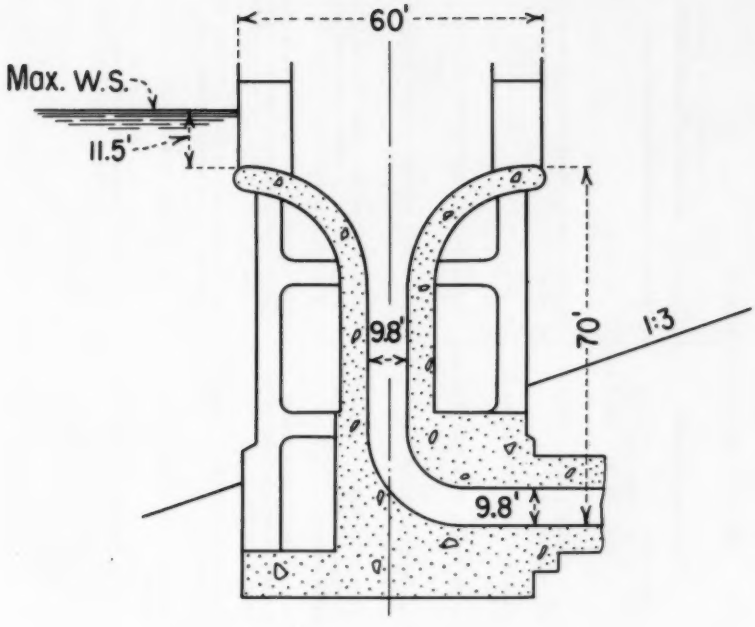
312 HEART BUTTE

Figure 21.—Spillway—Heart Butte Dam



SHADEHILL

Figure 22.—Spillway—Shade Hill Dam



AKONGTIEN

Figure 23.—Spillway—Akongtien Dam

Table 1

MORNING-GLORY SHAFT SPILLWAYS

Dam	Location	References to literature	References for correspondence
Owyhee	Owyhee Project--Idaho	Reclamation Era, Vol 30, No 8, Aug 1940, Page 226, Power Plant Engineering, Vol 37, Nov 1933, Page 482, HYD-159	Regional Director, Bureau of Reclamation, Boise, Idaho
Gibson	Sun River Project-Montana	HYD-159, Dams and Control Works, 1929, Page 79	Regional Director, Bureau of Reclamation, Billings, Montana
Sulak	Russia	Engineering News-Record, October 17, 1935	
Guernsey	North Platte Project--Nebraska	Dams and Control works, 1929, Page 55	Regional Director, Bureau of Reclamation, Denver, Colorado
Davis Bridge	On Deerfield River near Whitingham, Vermont	Trans ASCE, Vol 88, 1925, Page 1	H. M. Nelson, New England Power Service Co., 441 Stuart Street, Boston 16, Mass.
Pleasant Hill	Mohican River near Perrysville, Ohio	Hydraulic Model Studies for Pleasant Hill Dam, May, 1935, Case School of Applied Science	Division Engineer, Ohio River Division, Corps of Engineers, U. S. Army, 536 U. S. Post Office Bldg, Cincinnati 1, Ohio
Kingsley	North Platte River near Ogallala, Nebraska	Report on Hydraulic Model Studies, Kestone Dam, Nov 1936, Case School of Applied Science	Chief Engineer, Central Nebraska Public Power and Irrigation District, Hastings, Nebraska
Bouquet Canyon	Bouquet Creek, 50 miles from Los Angeles	Civil Engineering, Vol 4, No 8, Aug 1934, Page 393	Chief Engineer, Dept of Water and Power, City of Los Angeles, Los Angeles 54, California
Ladybower	Derwent River in Derbyshire, England	The Engineer, Vol 168, Nov 3, 1939, Page 440	G. H. Hill and Sons, 51 Mosley St., Manchester 2, England
Jubilee	Hong Kong	Experiments on Bellmouth and Siphon Bellmouth overflow spillways, by Geoffrey Morse Binnie, Journal Institute of Civil Engineer, Vol 10, Nov 1938, Page 65	W. J. E. Binnie, Binnie, Deacon and Gourley, Artillery House, Artillery Row, Victoria Street, Westminster, S. W. England

Dam	Location	References to literature	References for correspondence
Taf Fechan	Wales	Trans of the Institute of Water Engineers, Vol XLII, 1937, Page 103	W. J. E. Binnie, Binnie, Deacon and Gourley, Artillery House, Artillery Row, Victoria St., Westminster, S. W. England
Silent Valley	Ireland	Trans of the Institute of Water Engineers, Vol XLII, 1937, Page 103	W. J. E. Binnie, Binnie, Deacon and Gourley, Artillery House, Artillery Row, Victoria St., Westminster, S. W. England
Pontian Ketchil	Jahore	Trans of the Institute of Water Engineers, Vol XLII, 1937, Page 103	W. J. E. Binnie, Binnie, Deacon and Gourley, Artillery House, Artillery Row, Victoria St., Westminster, S. W. England
Burnhope	Durham County, England	Trans of the Institute of Water Engineers, Vol XLII, 1937, Page 103	W. J. E. Binnie, Binnie, Deacon and Gourley, Artillery House, Artillery Row, Victoria St., Westminster, S. W. England
Manuherikia Falls Dam	New Zealand	Trans of the Institute of Water Engineers, Vol XLII, 1937, Page 103	J. W. Ridley, Hydro-electric Design Office, Ministry of Works, Wellington, New Zealand
Bassano Power Canal	Northern Italy	Giornale del Genio Civile, July 31, 1917, Page 341	
Heart Butte	North Dakota		Regional Director, Bureau of Reclamation, Billings Montana
Hungry Horse	Montana		Regional Director, Bureau of Reclamation, Billings Montana
South Holston	South Holston River, Tennessee		Chief Engineer, Tennessee Valley Authority, Knoxville, Tennessee
Watauga	Watauga River, Tennessee		Chief Engineer, Tennessee Valley Authority, Knoxville, Tennessee
Akongtien	South Taiwan		Y. C. Chu, Engineer in charge
Lumot	Philippine Islands		Filemon C. Rodriguez, General Manager, National Power Corporation, Natividad Building, Manila, Republic of Philippines
LaRegadera	Bogota, Colombia, South America		F. Wiesner Rozo, Superintendent, Acueducto Municipal de Bogota, Bogota, Colombia, South America

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